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general operating principles

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of the A-1

GUN·BOMB·ROCKET SIGHT

by

A.D. Ehrenfried

INSTRUMENTATION LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Massachusetts

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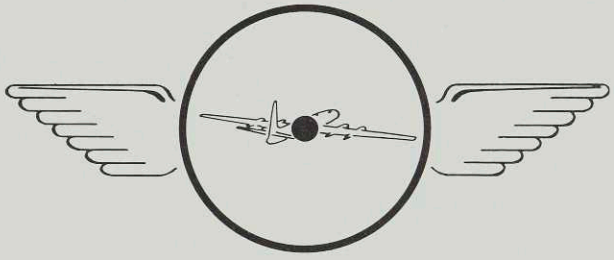

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approved: C.S. Draper

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DIRECTOR

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A. D. E.

TABLE OF CONTENTS

	Page
INTRODUCTION	1
1. GUNFIRE CONTROL	5
1:1 Required Corrections and Their Generation	5
1:1:1 Lead	5
1:1:2 Gravity-Drop	9
1:1:3 Velocity-Jump	13
1:1:4 Cross-Roll	15
1:2 Gunfire Calibration	19
1:2:1 General	19
1:2:2 Prediction Sensitivity Calibration	20
1:2:3 Special Characteristics of the Problem	21
2. ROCKETFIRE CONTROL	25
3. BOMBING OPERATION	27
3:1 Deflection Bombing System	27
3:2 Elevation Bombing System	28
BIBLIOGRAPHY	33

LIST OF ILLUSTRATIONS

Fig. No.	Title	Page
1	Important Elements of the A-1 Gun-Bomb-Rocket Sight in a Fixed-Gun Fighter	3
2	Corrections Generated by the A-1 Gun-Bomb-Rocket Sight	4
3	Lead Angle Resulting from Target Motion	5
4	Elevation and Deflection Lead Computing Equipment	7
5	Generation of Prediction Sensitivity Current from Range and Air Density Inputs	8
6	Gravity-Drop Curvature of Projectile Path	9
7	Unbalanced Mass Accelerometer on Elevation Gyro Gimbal	10
8	Velocity-Jump Effect	11
9	Velocity-Jump Resulting from Acceleration of Fighter in a Coordinated Turn	12
10	Cross-Roll Effect Resulting from Rolling Motion of Turning Fighter	14
11	Action of Deflection Gyroscope to Introduce Deflection Cross-Roll Correction	17
12	Three Important Characteristics of the A-1 Gunsight Problem	22
13	Rocketfire with the A-1 Sight	24
14	Method of A-1 Sight Bombing in Deflection	26
15	Method of A-1 Sight Bombing in Elevation	29
16	Airspeed-Controlled Bombing Accelerometer	30

frontispiece

GENERAL OPERATING PRINCIPLES

of the

A-1 GUN-BOMB-ROCKET SIGHT

INTRODUCTION

The A-1 Gun-Bomb-Rocket Sight is employed in fixed-gun fighter aircraft to control gunfire, rocketfire and the dropping of bombs. All three types of missiles are aimed by positioning the fighter aircraft itself. In doing this the pilot is guided by an illuminated circular reticle and dot projected onto the windshield. This tracking index is held continuously on the target by the pilot, causing the fighter aircraft to move along a lead-pursuit course during gunfire and rocketfire operation.

Important elements of the A-1 Gun-Bomb-Rocket Sight are shown in Fig. 1. A radar antenna for receiving radar range information is located in the nose of the aircraft. The prediction computer, electronic unit and radar components are mounted just forward of the pilot's compartment. A sight head located in front of the pilot contains the optical system for projecting the tracking reticle onto the windshield.

The function of the computing instruments of the A-1 Sight is to determine continuously the correct offset angle between the tracking reticle and the line along which the missiles are launched. This angle measured from the tracking line (the line through the tracking index) to the axis of the guns or rocket launcher is called the prediction angle and is shown in Fig. 1.

In the control of gunfire and rocketfire, corrections are generated in the A-1 Sight for lead, gravity-drop and velocity-jump. These three angular corrections are added together as shown in Fig. 2 to form the prediction angle. The lead angle lies in the plane of target motion. Gravity-drop correction is in the plane of gravity, vertical to the Earth. Velocity-jump correction is in the plane of symmetry of the fighter aircraft. An additional cross-roll correction is made for rolling of the fighter about its gun line while making an attack.

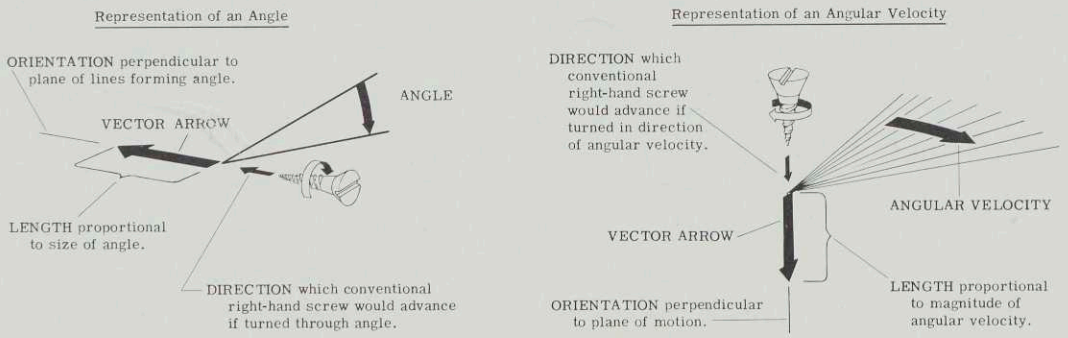
Introduction

It is found convenient in the A-1 Gunsight to generate fire control corrections relative to elevation and deflection axes fixed in the aircraft; these axes are shown in Fig. 1. It can be seen that up and down motions relative to the fighter represent rotations about the elevation axis; and sidewise, or left and right, motions represent rotations about the deflection axis.* Inputs are measured with respect to the elevation and deflection directions and are employed in separate elevation and deflection computing systems. The elevation prediction system is mechanized and adjusted to produce lead, gravity-drop, velocity-jump and cross-roll corrections. The deflection prediction system yields corrections for lead, gravity-drop and cross-roll. The prediction outputs of the elevation and deflection computations are finally combined by the mirror system in the sight head to provide the resultant prediction angle.

During automatic ranging, the diameter of the circular tracking reticle (in mils of angle subtended) is made proportional to the ratio of a wing-span setting to the measured range to the target. Stadiametric range information can be introduced manually to the sight by (1) adjusting the wing-span setting in accordance with the type of target being tracked and (2) turning a throttle hand-control continually to make reticle size correspond to target size.

In Sec. 1:1 of this report, the general methods are described for generating lead, gravity-drop, velocity-jump and cross-roll corrections for gunfire operation. The overall gunfire calibration procedure is set forth in Sec. 1:2. In Secs. 2 and 3, the principles of rocketfire and bombing are summarized. More detailed treatments of all these subjects may be found in the A-1 Gunsight Volumes I and II prepared by the M. I. T. Instrumentation Laboratory.

* In this report, angles and angular velocities are represented in the following manner by arrows (vectors) along the elevation and deflection axes:


Representation of an Angle
ORIENTATION perpendicular to plane of lines forming angle.
ANGLE
VECTOR ARROW
LENGTH proportional to size of angle.
DIRECTION which conventional right-hand screw would advance if turned through angle.
Representation of an Angular Velocity
DIRECTION which conventional right-hand screw would advance if turned in direction of angular velocity.
ANGULAR VELOCITY
VECTOR ARROW
LENGTH proportional to magnitude of angular velocity.
ORIENTATION perpendicular to plane of motion.

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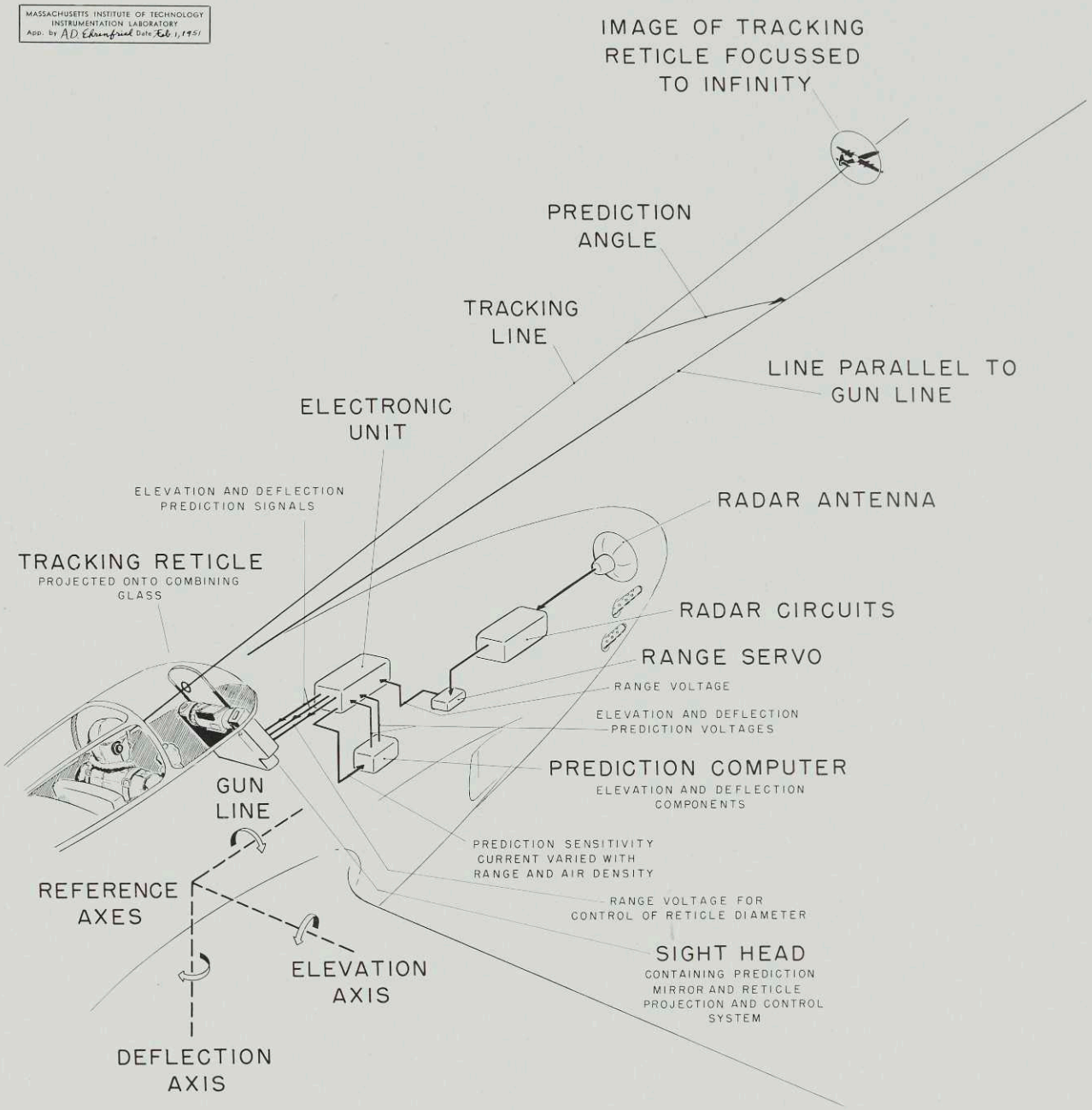

Fig. 1 IMPORTANT ELEMENTS OF THE A-1 GUN-BOMB-ROCKET SIGHT IN A FIXED-GUN FIGHTER

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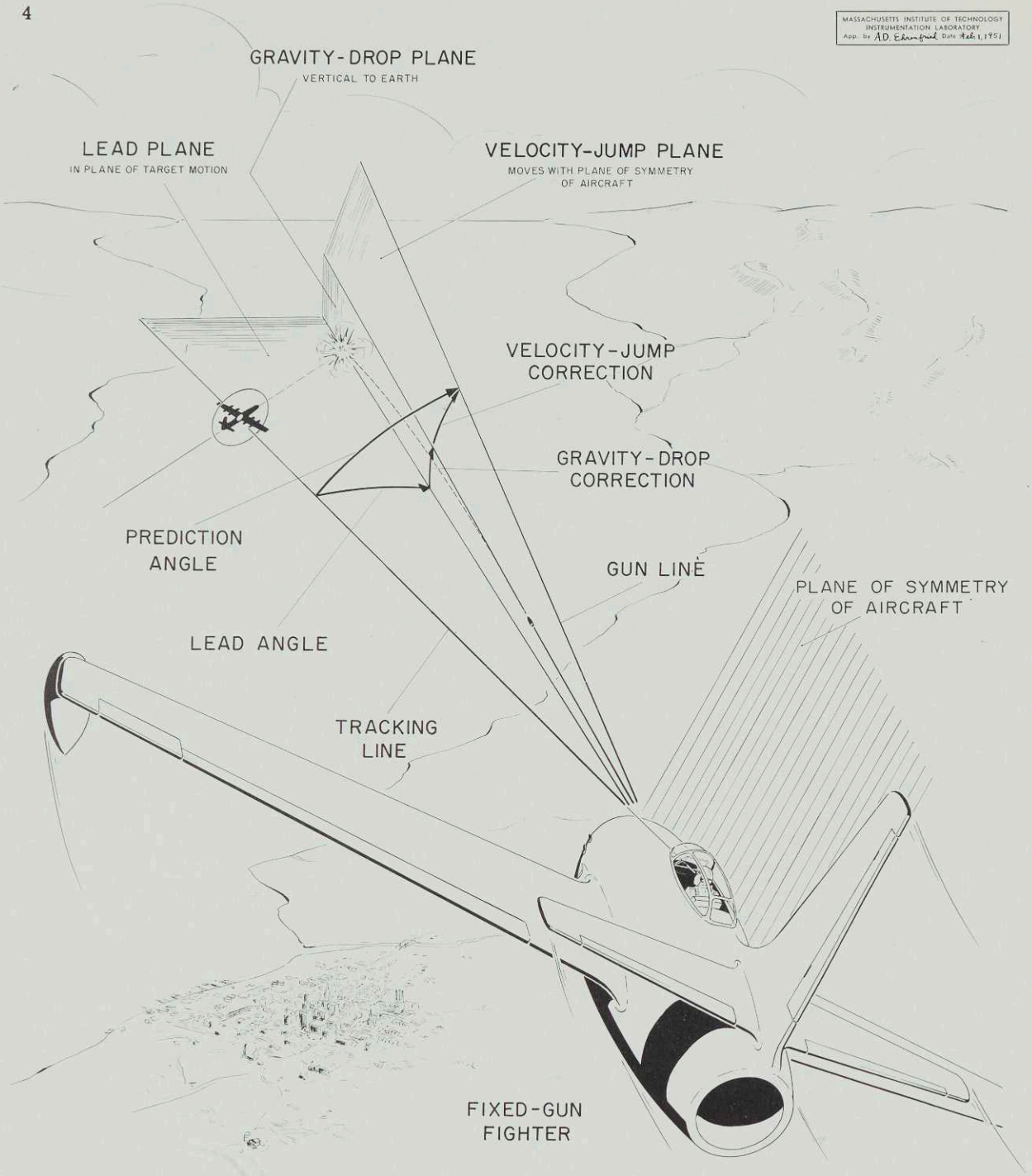

Fig. 2 CORRECTIONS GENERATED BY THE A-1 GUN-BOMB-ROCKET SIGHT
The total of corrections is the prediction angle measured from tracking line to gun line

I. GUNFIRE CONTROL

The most important use of the A-1 Gun-Bomb-Rocket Sight is for the accurate control of gunfire against high-speed enemy aircraft. For this type of attack, the fighter carries from four to six caliber 0.50 machine guns in the nose or wings, and fires M8-API (armor-piercing incendiary) rounds. The offset angle between the guns and the tracking line that will result in maximum damage to a selected target is computed by the prediction mechanisms described in this section.

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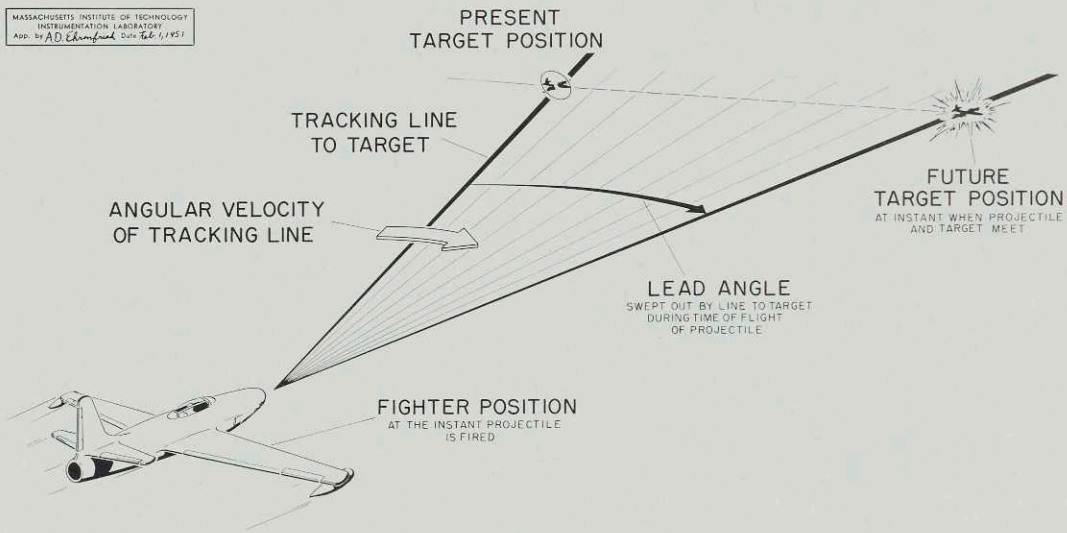

Fig. 3 LEAD ANGLE RESULTING FROM TARGET MOTION

1:1 REQUIRED CORRECTIONS AND THEIR GENERATION

1:1:1 Lead

Lead is the largest correction required by the air-to-air fire control problem. This correction for target motion is necessary because the projectile takes a finite time to travel to the target, and the guns must therefore be aimed ahead of the target if hits are to be scored. Lead angles may be of the order of 100 mils (milliradians) or more for the A-1 gunfire problem. As shown in Fig. 3 the lead angle can be defined as the angle swept out by the line to the target during the time the projectile is in flight. This

angle is essentially computed in the A-1 Gunsight as the product of tracking-line angular velocity and a modified time-of-flight variable called "prediction sensitivity". The lead computation is broken down into an elevation computation, a deflection computation and the generation of a prediction sensitivity current.

Elevation Lead Computation: The lead computing equipment shown in Fig. 4 consists of elevation and deflection computers which are aligned with a set of reference axes. The input axis of the elevation gyroscope is aligned with the elevation axis to receive the elevation component of gun-line angular velocity. Through a mechanical linkage, this gyro applies a torque, proportional to angular velocity, to the computer shaft. In response to this torque, the shaft turns through an angle dependent both upon the size of the torque and upon the "stiffness" coefficient of a microsyn elastic restraint motor. The torque stiffness of the elastic restraint, in torque per unit angle, is controlled by the prediction sensitivity current introduced to the windings of the elastic restraint motor. The magnitude of this current is related approximately to the reciprocal of projectile time of flight. With the elevation gyro torque proportional to elevation angular velocity and the elastic restraint related to projectile time of flight, the resultant angular displacement of the computer shaft is made directly proportional to the product of these two quantities and thus to the elevation component of lead angle.

Also attached to the elevation shaft is a viscous damper consisting of a cup which moves in a close-fitting well, filled with damping fluid. The viscous friction torque introduced by this damper opposes rotation of the computer shaft. In doing this the damper (1) smooths and stabilizes the prediction computation and (2) corrects for the fact that the gyros, which are fixed relative to the guns, measure gun-line angular velocity instead of tracking-line angular velocity.

The elevation microsyn pickoff in Fig. 4 provides the electronic unit with a voltage proportional to the resultant elevation shaft angle position. As shown later, gravity-drop and velocity-jump elevation corrections are also generated in the elevation computer.

Deflection Lead Computation: The deflection computer shown in Fig. 4 employs a gyroscope, a microsyn elastic restraint motor, a viscous damper and a microsyn pick-off to generate the deflection component of lead angle. The input axis of the deflection gyro, instead of being aligned with the deflection axis, is displaced at a fixed angle of 10° to provide the cross-roll correction described in Sec. 1:1:4. The angular velocity

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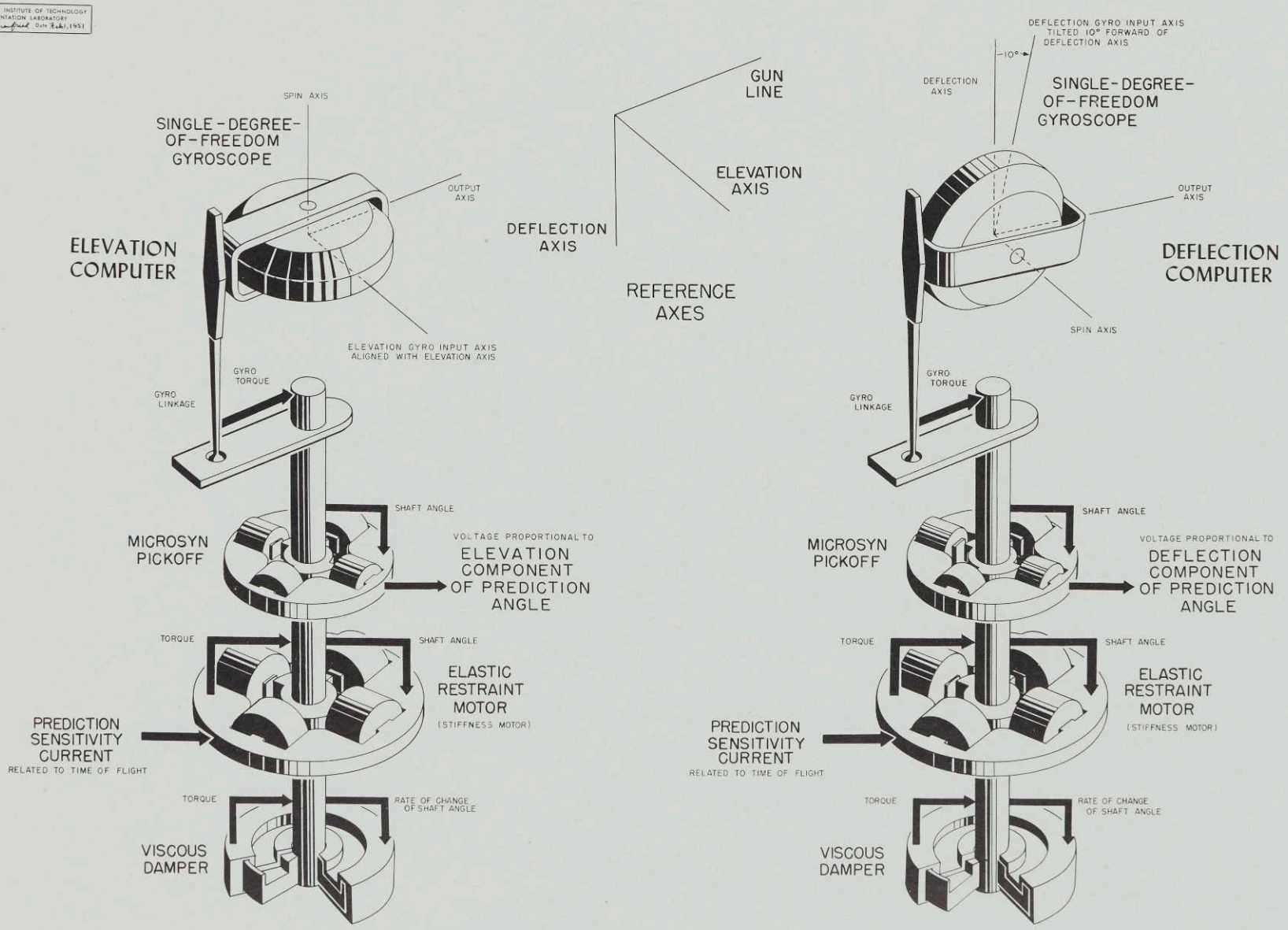


Fig. 4 ELEVATION AND DEFLECTION LEAD COMPUTING EQUIPMENT
Arrows show information flow

received by the deflection gyroscope, however, is 98.5 percent of the angular velocity about the deflection axis and is an acceptable input to the deflection lead computation. The deflection elastic restraint motor also receives the prediction sensitivity current related to projectile time of flight. The sum of the gyro, elastic restraint and viscous damper torques results in a displacement of the deflection computer shaft directly proportional to the deflection component of lead angle. The pickoff provides the required deflection voltage.

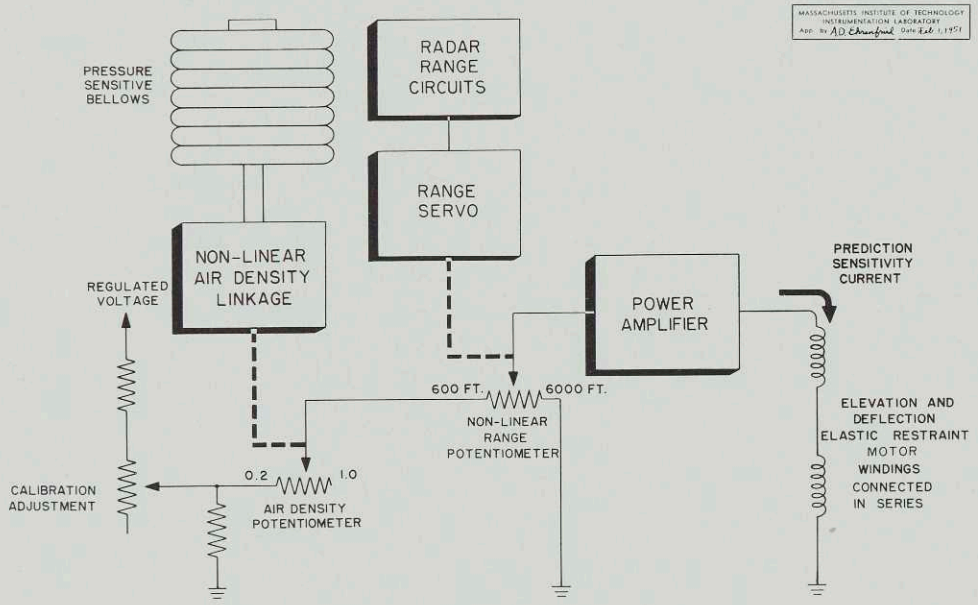
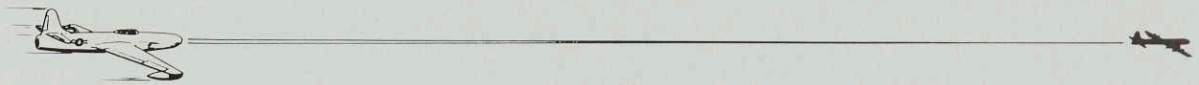


Fig. 5 GENERATION OF PREDICTION SENSITIVITY CURRENT FROM RANGE AND AIR DENSITY INPUTS

Prediction Sensitivity Current: An important input to the lead computation is the prediction sensitivity current which relates both elevation and deflection elastic restraints to a family of calibration curves derived by the procedure of Sec. 1:2. The present range from the fighter to the target and the relative air density are the two inputs to the prediction sensitivity computation and enter into the generation of the prediction sensitivity current as shown in Fig. 5. The tap of the air density potentiometer is moved by a bellows assembly and that of the range potentiometer by the range servo. The resultant prediction sensitivity current out of the power amplifier goes to the windings of the elevation and deflection elastic restraint (stiffness) motors connected in series.



1:1:2 Gravity-Drop

The projectile in free flight, being attracted toward the center of the earth, undergoes a downward acceleration due to gravity. The resultant projectile path has the gravity-drop curvature shown in Fig. 6. Correction for this gravity effect is made by raising the guns in a plane vertical to the earth. The gravity-drop correction is normally from 2 to 15 mils.

In Fig. 6 it can be seen that curvature of the projectile path is caused by the component of gravity perpendicular to the gun line. For the fighter flying with wings level, the input to the gravity-drop correction is the acceleration of gravity along the deflection axis. The correction for gravity-drop, however, is made by raising the guns about the elevation axis. When the fighter flies with wings approximately level, this elevation gravity correction is the only gravity component required.

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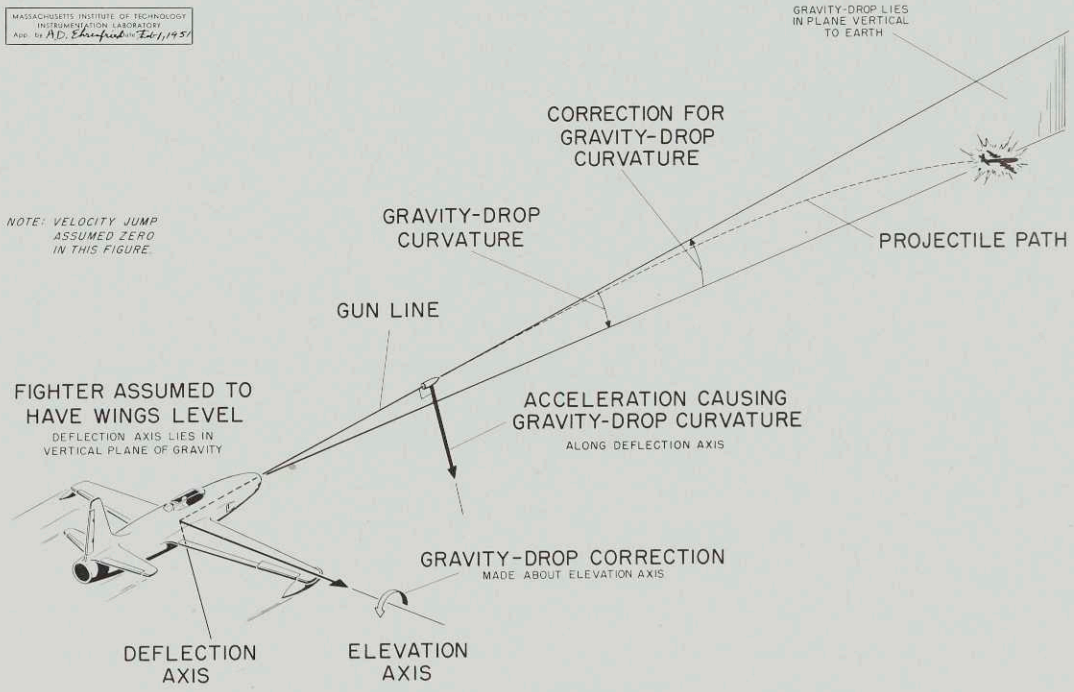
GRAVITY-DROP LIES IN PLANE VERTICAL TO EARTH
CORRECTION FOR GRAVITY-DROP CURVATURE
NOTE: VELOCITY JUMP ASSUMED ZERO IN THIS FIGURE.
GRAVITY-DROP CURVATURE
PROJECTILE PATH
GUN LINE
FIGHTER ASSUMED TO HAVE WINGS LEVEL
DEFLECTION AXIS LIES IN VERTICAL PLANE OF GRAVITY
ACCELERATION CAUSING GRAVITY-DROP CURVATURE
ALONG DEFLECTION AXIS
GRAVITY-DROP CORRECTION
MADE ABOUT ELEVATION AXIS
DEFLECTION AXIS
ELEVATION AXIS

Fig. 6 GRAVITY-DROP CURVATURE OF PROJECTILE PATH
Effect is caused by gravity acceleration along deflection axis. Correction is made about elevation axis

The accelerometer shown in Fig. 7 is employed in the A-1 Gunsight to provide the elevation gravity-drop correction. It consists of an unbalanced mass attached to the elevation gyroscope gimbal and is oriented to receive acceleration along the deflection axis. In the presence of gravity the accelerometer mass applies a correction torque to the elevation gyro assembly. This torque is transmitted through the gyro linkage to the elevation computer shaft. The accelerometer of Fig. 7 therefore receives the required deflection component of gravity acceleration and provides an elevation gravity-drop correction about the elevation axis.

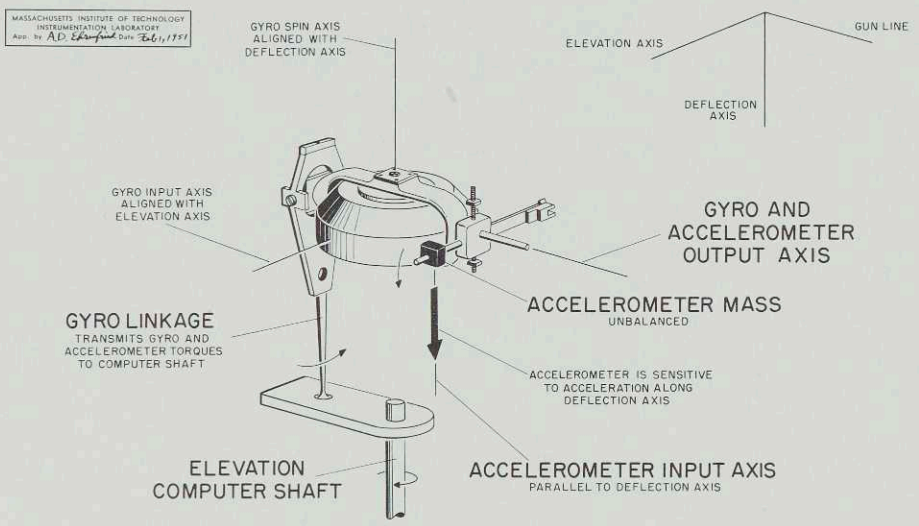

Fig. 7 UNBALANCED MASS ACCELEROMETER ON ELEVATION GYRO GIMBAL
Receives acceleration along deflection axis and provides correction for gravity-drop and velocity-jump about elevation axis

When the wings of the fighter are not level, a deflection gravity-drop correction is required in addition to the elevation component. Since the fighter is flown in a "coordinated" manner with zero resultant acceleration parallel to the wings (i.e., along the elevation axis), an unbalanced mass accelerometer can receive no acceleration input and cannot be used to provide the deflection gravity correction. Thus, instead of being explicitly instrumented by the use of an accelerometer mechanism, a compensation is made for deflection gravity-drop in the calibration process of Section 1:2.

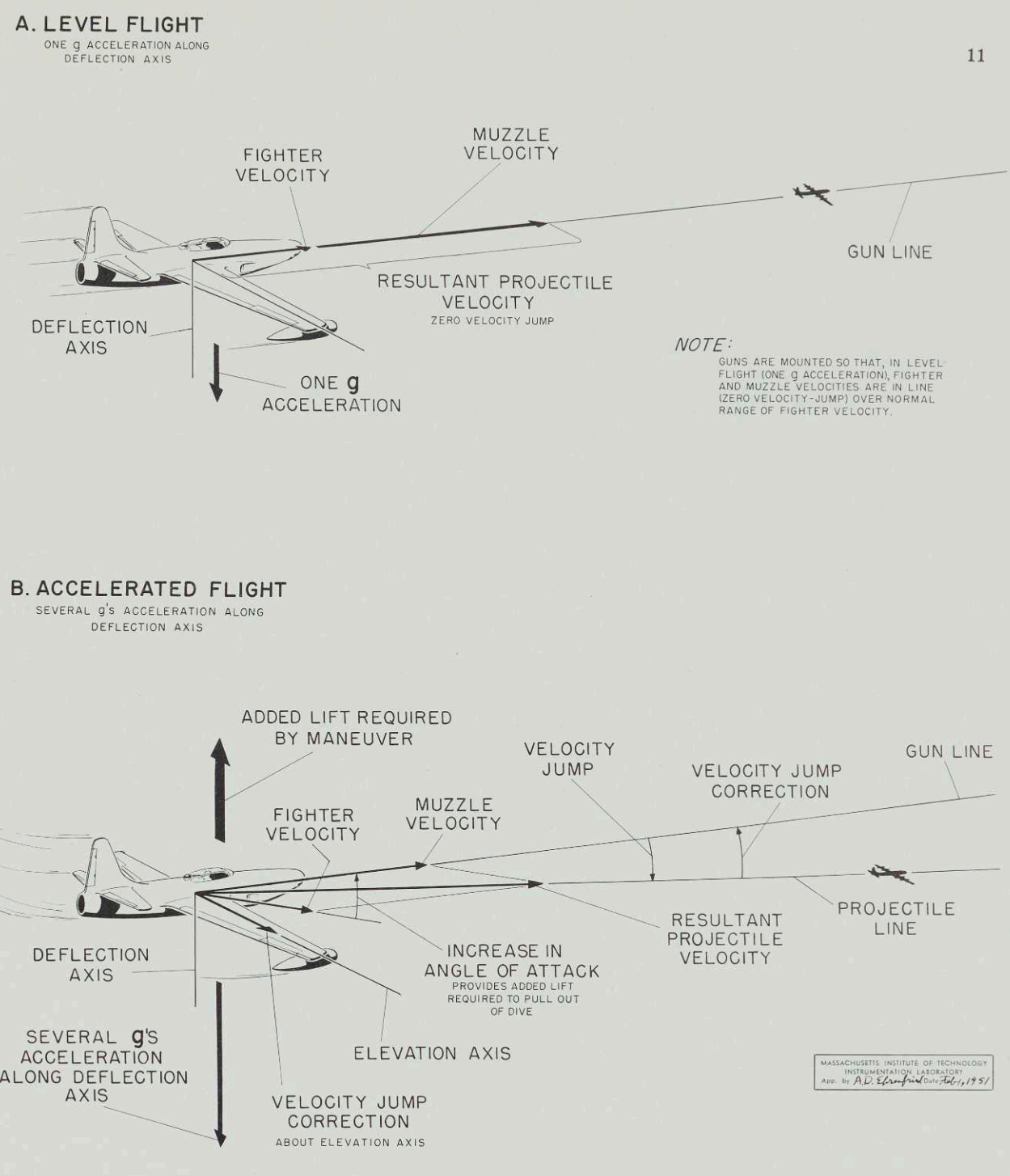
A. LEVEL FLIGHT
ONE g ACCELERATION ALONG DEFLECTION AXIS
FIGHTER VELOCITY
MUZZLE VELOCITY
GUN LINE
RESULTANT PROJECTILE VELOCITY
ZERO VELOCITY JUMP
DEFLECTION AXIS
ONE g ACCELERATION
NOTE:
GUNS ARE MOUNTED SO THAT, IN LEVEL FLIGHT (ONE g ACCELERATION), FIGHTER AND MUZZLE VELOCITIES ARE IN LINE (ZERO VELOCITY-JUMP) OVER NORMAL RANGE OF FIGHTER VELOCITY.
B. ACCELERATED FLIGHT
SEVERAL g's ACCELERATION ALONG DEFLECTION AXIS
ADDED LIFT REQUIRED BY MANEUVER
VELOCITY JUMP
VELOCITY JUMP CORRECTION
GUN LINE
FIGHTER VELOCITY
MUZZLE VELOCITY
PROJECTILE LINE
RESULTANT PROJECTILE VELOCITY
DEFLECTION AXIS
INCREASE IN ANGLE OF ATTACK
PROVIDES ADDED LIFT REQUIRED TO PULL OUT OF DIVE
SEVERAL g'S ACCELERATION ALONG DEFLECTION AXIS
ELEVATION AXIS
VELOCITY JUMP CORRECTION
ABOUT ELEVATION AXIS
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Fig. 8 VELOCITY-JUMP EFFECT

Results from increased angle-of-attack required by acceleration in excess of one gravity along the deflection axis. Correction is made about the elevation axis

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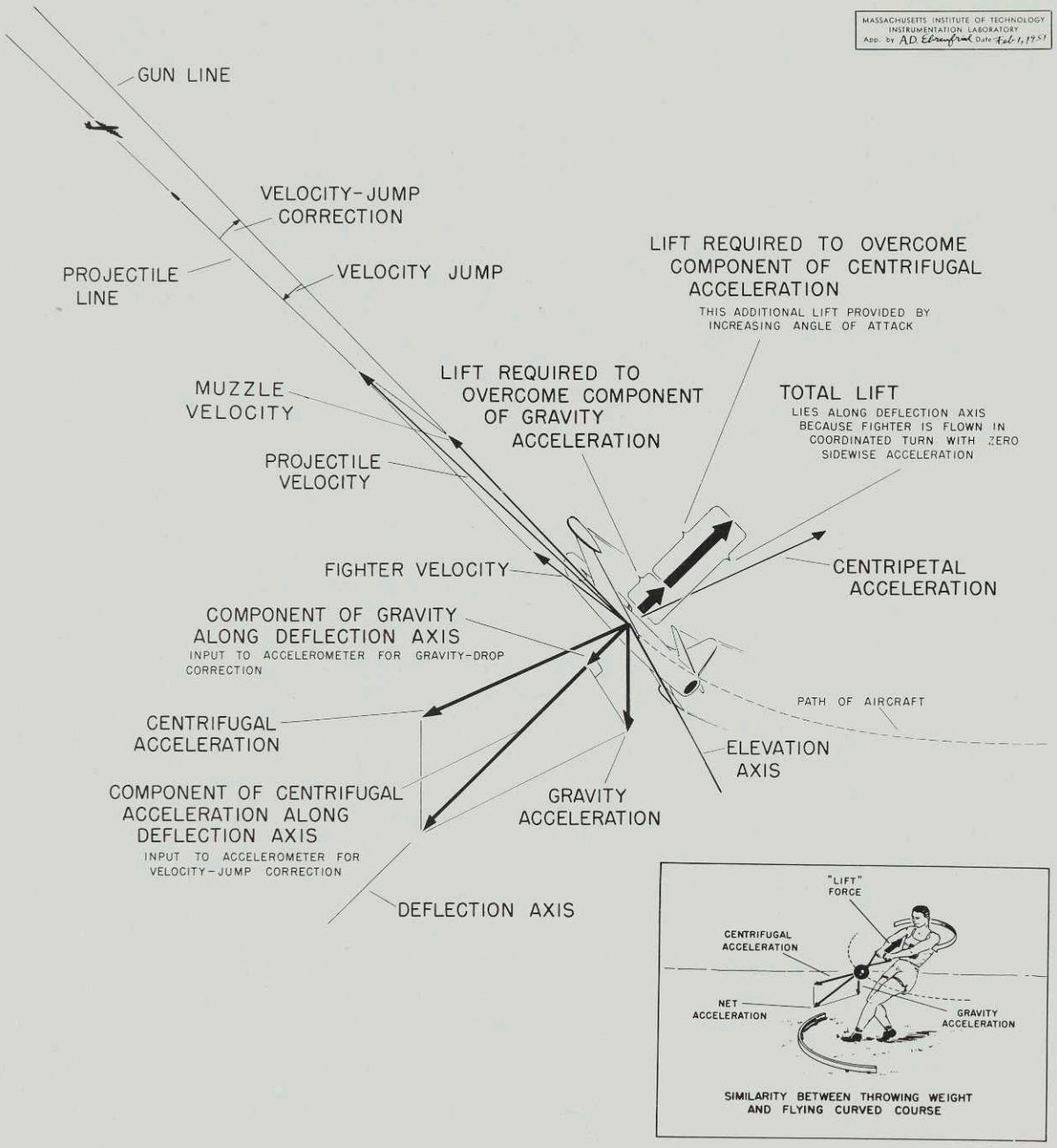
GUN LINE
VELOCITY-JUMP CORRECTION
PROJECTILE LINE
VELOCITY JUMP
LIFT REQUIRED TO OVERCOME COMPONENT OF CENTRIFUGAL ACCELERATION
THIS ADDITIONAL LIFT PROVIDED BY INCREASING ANGLE OF ATTACK
MUZZLE VELOCITY
LIFT REQUIRED TO OVERCOME COMPONENT OF GRAVITY ACCELERATION
TOTAL LIFT
LIES ALONG DEFLECTION AXIS BECAUSE FIGHTER IS FLOWN IN COORDINATED TURN WITH ZERO SIDEWISE ACCELERATION
PROJECTILE VELOCITY
FIGHTER VELOCITY
CENTRIPETAL ACCELERATION
COMPONENT OF GRAVITY ALONG DEFLECTION AXIS
INPUT TO ACCELEROMETER FOR GRAVITY-DROP CORRECTION
PATH OF AIRCRAFT
CENTRIFUGAL ACCELERATION
ELEVATION AXIS
COMPONENT OF CENTRIFUGAL ACCELERATION ALONG DEFLECTION AXIS
INPUT TO ACCELEROMETER FOR VELOCITY-JUMP CORRECTION
GRAVITY ACCELERATION
DEFLECTION AXIS
"LIFT" FORCE
CENTRIFUGAL ACCELERATION
NET ACCELERATION
GRAVITY ACCELERATION
SIMILARITY BETWEEN THROWING WEIGHT AND FLYING CURVED COURSE

Fig. 9 VELOCITY-JUMP RESULTING FROM ACCELERATION OF FIGHTER IN A COORDINATED TURN

Similarity between accelerations associated with weight thrower are shown

1:1:3 Velocity-Jump

A projectile fired from a moving fighter enters the air mass with a velocity that is the vector sum of muzzle velocity and fighter velocity. When the gun is pointing in the direction the aircraft is moving, as in Fig. 8-A, the projectile departs in normal fashion along the gun line, and with a velocity equal to the algebraic sum of fighter and muzzle velocities. When the angle of attack of the fighter is increased, as in Fig. 8-B, the gun line is elevated above the line of fighter motion and the projectile departs along the projectile line with the resultant projectile velocity shown. The angle measured from the gun line to the projectile line is called velocity-jump and is usually from 10 to 40 mils in size. Since the fighter is normally flown without yaw, the velocity-jump angle lies in the aircraft plane of symmetry, and only an elevation velocity-jump correction is required.

Large angles of attack occur when the fighter flies in a curved path, and it is under this condition that large velocity-jump corrections are required. In Fig. 8-B the aircraft is shown pulling out of a dive and undergoing several g's acceleration along the deflection axis. To provide the additional lift required to perform this maneuver, the angle of attack of the aircraft must be increased, placing the gun line above the fighter velocity vector. Because of the resulting velocity-jump, the projectile proceeds along the projectile line which is below the gun line. To correct for this, the gun line must be raised about the elevation axis by the velocity-jump correction shown.

The most common maneuver requiring velocity-jump correction is the coordinated turn shown in Fig. 9. This turning motion results in a component of centrifugal acceleration along the deflection axis, as well as the component of gravity acceleration. The increased lift force required to make the turn is much like the force exerted by the weight thrower to keep the ball moving in a horizontal circle (See insert of Fig. 9). To provide the added lift required, the aircraft angle of attack must be increased and the nose of the fighter (and gun line) raised above the fighter velocity vector. The projectile velocity vector is essentially pulled downward by the fighter velocity vector, and the guns must be raised about the elevation axis by the amount of velocity-jump correction.

It is important to note that both velocity-jump and elevation gravity-drop result from downward acceleration along the deflection axis, and that both are corrected by raising the guns about the elevation axis. It is also significant that the relative magnitudes of the two corrections (in correction-angle required per unit of acceleration), while not being identical, are at least comparable.

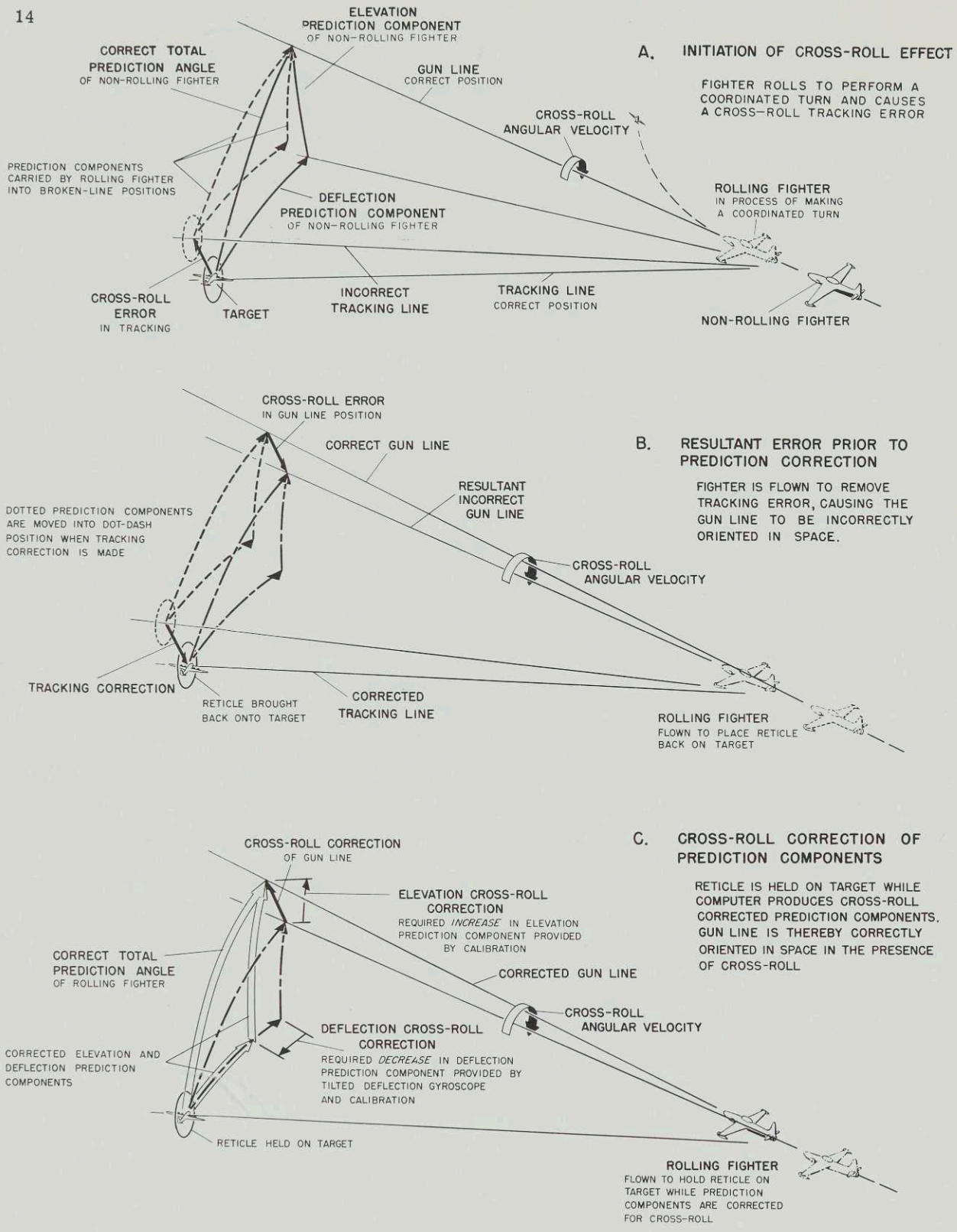
ELEVATION PREDICTION COMPONENT OF NON-ROLLING FIGHTER
CORRECT TOTAL PREDICTION ANGLE OF NON-ROLLING FIGHTER
GUN LINE CORRECT POSITION
A. INITIATION OF CROSS-ROLL EFFECT
FIGHTER ROLLS TO PERFORM A COORDINATED TURN AND CAUSES A CROSS-ROLL TRACKING ERROR
CROSS-ROLL ANGULAR VELOCITY
PREDICTION COMPONENTS CARRIED BY ROLLING FIGHTER INTO BROKEN-LINE POSITIONS
DEFLECTION PREDICTION COMPONENT OF NON-ROLLING FIGHTER
ROLLING FIGHTER IN PROCESS OF MAKING A COORDINATED TURN
CROSS-ROLL ERROR IN TRACKING
TARGET
INCORRECT TRACKING LINE
TRACKING LINE CORRECT POSITION
NON-ROLLING FIGHTER
CROSS-ROLL ERROR IN GUN LINE POSITION
CORRECT GUN LINE
B. RESULTANT ERROR PRIOR TO PREDICTION CORRECTION
FIGHTER IS FLOWN TO REMOVE TRACKING ERROR, CAUSING THE GUN LINE TO BE INCORRECTLY ORIENTED IN SPACE.
RESULTANT INCORRECT GUN LINE
DOTTED PREDICTION COMPONENTS ARE MOVED INTO DOT-DASH POSITION WHEN TRACKING CORRECTION IS MADE
CROSS-ROLL ANGULAR VELOCITY
TRACKING CORRECTION
RETICLE BROUGHT BACK ONTO TARGET
CORRECTED TRACKING LINE
ROLLING FIGHTER FLOWN TO PLACE RETICLE BACK ON TARGET
CROSS-ROLL CORRECTION OF GUN LINE
C. CROSS-ROLL CORRECTION OF PREDICTION COMPONENTS
RETICLE IS HELD ON TARGET WHILE COMPUTER PRODUCES CROSS-ROLL CORRECTED PREDICTION COMPONENTS. GUN LINE IS THEREBY CORRECTLY ORIENTED IN SPACE IN THE PRESENCE OF CROSS-ROLL
ELEVATION CROSS-ROLL CORRECTION
REQUIRED INCREASE IN ELEVATION PREDICTION COMPONENT PROVIDED BY CALIBRATION
CORRECT TOTAL PREDICTION ANGLE OF ROLLING FIGHTER
CORRECTED GUN LINE
CROSS-ROLL ANGULAR VELOCITY
DEFLECTION CROSS-ROLL CORRECTION
REQUIRED DECREASE IN DEFLECTION PREDICTION COMPONENT PROVIDED BY TILTED DEFLECTION GYROSCOPE AND CALIBRATION
CORRECTED ELEVATION AND DEFLECTION PREDICTION COMPONENTS
RETICLE HELD ON TARGET
ROLLING FIGHTER FLOWN TO HOLD RETICLE ON TARGET WHILE PREDICTION COMPONENTS ARE CORRECTED FOR CROSS-ROLL

Fig. 10 CROSS-ROLL EFFECT RESULTING FROM ROLLING MOTION OF TURNING FIGHTER

Combined Turning, Tracking And Prediction Correction Operations Are Shown In Sequence

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Because of these similarities, the accelerometer mechanism shown in Fig. 7 is used to correct for both the elevation component of gravity-drop and for velocity-jump. The unbalanced mass on the elevation gyro gimbal receives the total acceleration along the deflection axis and does not distinguish between acceleration due to gravity and kinematic acceleration due to motion. Since both accelerations enter the same correction system, however, it is unnecessary to distinguish between them. The gravity acceleration acting on the accelerometer produces the elevation gravity-drop correction, and the additional acceleration caused by the turning motion of the fighter results in a compensation for velocity-jump. Adjustment in the size of the combined correction is made in the calibration.

1:1:4 Cross-Roll

In addition to rotations of the fighter about the elevation and deflection axes producing lead, there are rotations about the gun line called cross-roll. Such rolling motion about the gun line carries the A-1 Sight and its elevation and deflection reference axes with it. As a result, the elevation and deflection components of prediction angle must change in magnitude if the correct orientation of the total prediction angle is to be maintained in space.

The elevation and deflection computers shown in Fig. 4 both employ viscous dampers. These resist motion of the computer shafts and thus prevent the components of prediction from changing as rapidly as they should. When the A-1 Sight is rotated about the gun line, the total prediction angle thus tends to be carried with it. If no correction is made, a cross-roll error appears which is due chiefly to the resultant misorientation of the prediction angle.

In Fig. 10 the fixed-gun fighter is shown attacking a target which moves from left to right. The sequence of operation is broken down into steps A, B and C. Steps A and B occur whether or not cross-roll correction exists; however, with a correction system the errors shown are kept negligibly small. Step C shows how correction of the prediction components results in the correct orientation of the gun line in the presence of cross-roll. With the A-1 Gunsight, the three steps of Fig. 10 occur essentially simultaneously, and appreciable cross-roll errors in gun-line position are never allowed to develop. The steps are shown in sequence in Fig. 10 for ease of explanation.

Cross-Roll Correction

The non-rolling fighter in Fig. 10-A displays the prediction components shown solid. To continue tracking the target, the fighter must go into a coordinated banking turn. As the fighter rolls to perform this maneuver, the prediction angle and its components rotate momentarily into the positions shown in broken outline. Without correction, a cross-roll error in tracking exists which may be large enough to make tracking difficult.

In Fig. 10-B the tracking correction is made by maneuvering the fighter to place the reticle back on target. By so doing, however, the gun line of the rolling fighter is incorrectly oriented in space. It is this gun-pointing error that causes a serious reduction in hits on the target. From Fig. 10-B it can be seen that if the guns are to be pointed correctly with the tracking reticle held on target the magnitudes of the elevation and deflection prediction components must be altered; i.e., they must be corrected for cross-roll.

Figure 10-C shows the elevation and deflection prediction corrections that return the gun line to its correct position in space with the reticle held on target. The elevation prediction component must be increased and the deflection prediction component decreased. These are the changes in prediction components that are resisted by the viscous dampers.

When the fighter commences to roll in a coordinated turn, the tracking reticle tends initially to be lifted above the target and to fall behind it. The elevation portion of this tracking error is easily corrected by a forward motion of the control stick. The necessary increase in elevation prediction angle is at least partially provided by a calibration adjustment made during the initial design of the A-1 Gunsight, as described in Sec. 1:2.

The deflection tracking error is less easily corrected since a conventional aircraft can be turned to left or right only by changing its angle of bank, and such action introduces an additional cross-roll error. By means of the deflection gyroscope with its tilted input axis, a reduction in the deflection prediction component is achieved which helps to bring the reticle back on target without the gun line being moved from its correct position. Thus the A-1 Gunsight provides a form of "aided tracking" in deflection in the presence of cross-roll. The manner in which the deflection gyroscope introduces a cross-roll correction is next described.

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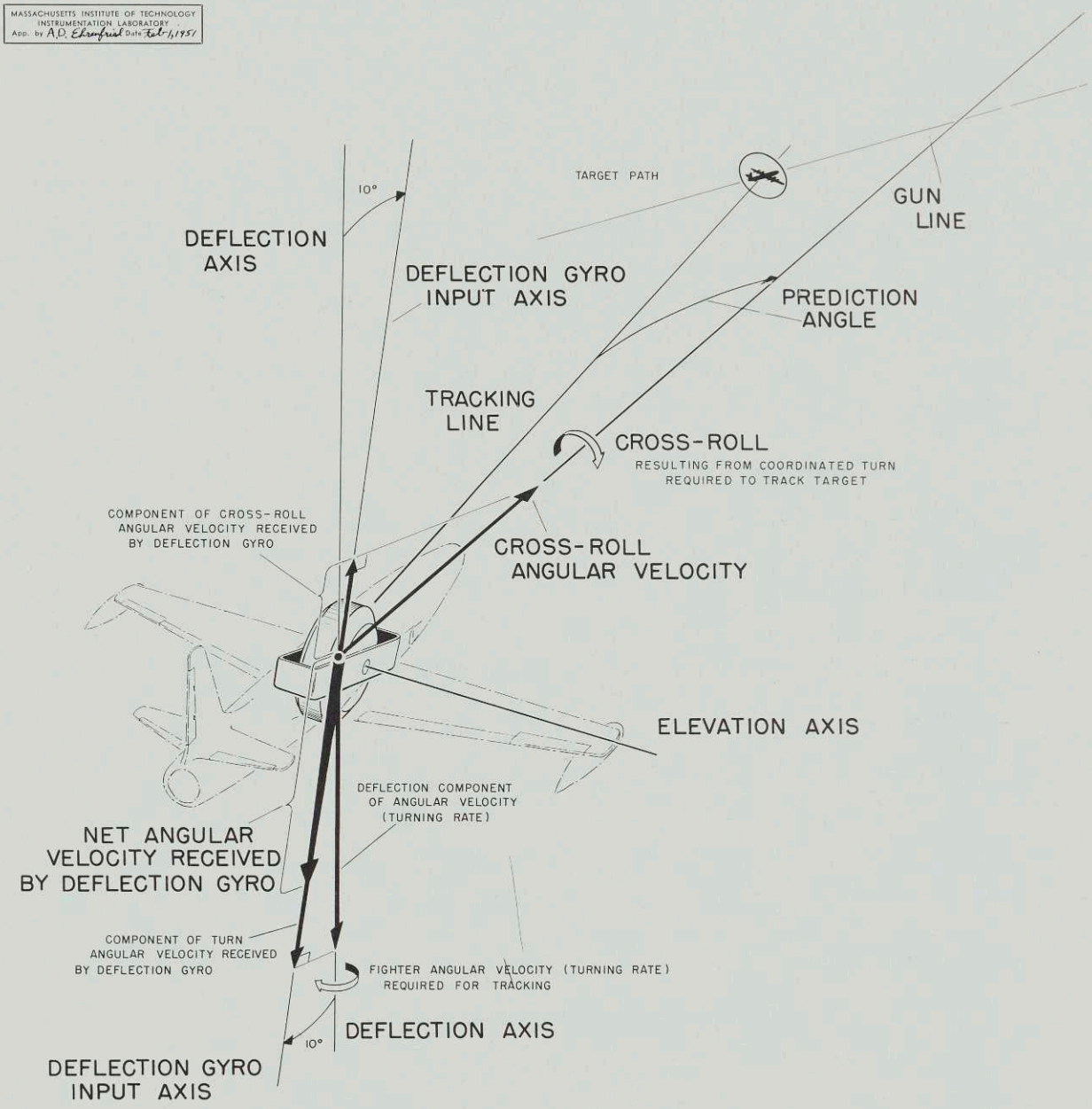
10°
DEFLECTION AXIS
TARGET PATH
GUN LINE
DEFLECTION GYRO INPUT AXIS
PREDICTION ANGLE
TRACKING LINE
CROSS-ROLL
RESULTING FROM COORDINATED TURN REQUIRED TO TRACK TARGET
COMPONENT OF CROSS-ROLL ANGULAR VELOCITY RECEIVED BY DEFLECTION GYRO
CROSS-ROLL ANGULAR VELOCITY
ELEVATION AXIS
DEFLECTION COMPONENT OF ANGULAR VELOCITY (TURNING RATE)
NET ANGULAR VELOCITY RECEIVED BY DEFLECTION GYRO
COMPONENT OF TURN ANGULAR VELOCITY RECEIVED BY DEFLECTION GYRO
FIGHTER ANGULAR VELOCITY (TURNING RATE) REQUIRED FOR TRACKING
10°
DEFLECTION AXIS
DEFLECTION GYRO INPUT AXIS

Fig. II ACTION OF DEFLECTION GYROSCOPE TO INTRODUCE DEFLECTION CROSS-ROLL CORRECTION

Deflection gyro displaced 10° receives component of cross-roll angular velocity which reduces deflection component of prediction as required

Cross-Roll Correction

As shown in Fig. 10 the deflection component of prediction angle must be reduced if the correct, rather than erroneous, total prediction angle is to be displayed by the rolling fighter. The reduction is achieved by mounting the deflection gyroscope with its input axis displaced 10 degrees forward of the deflection axis as shown in Figs. 4 and 11. In this position the deflection gyro receives components of both elevation and cross-roll angular velocities. For the 10-degree angle of tilt, the gyro receives 98.5 percent of the deflection angular velocity and 17.5 percent of the cross-roll angular velocity.

Components of angular velocity are resolved along the input axis of the deflection gyro in Fig. 11. It is important to note that the component of cross-roll angular velocity received is opposed to the turn angular velocity received. The cross-roll angular velocity thus reduces the net angular velocity into the deflection lead system and causes a reduction in the deflection component of prediction angle as is required.

An additional requirement met is that the amount of the deflection cross-roll correction is directly proportional to the cross-roll angular velocity. The deflection cross-roll correction should also be made directly proportional to the elevation component of the prediction angle. However, to simplify the instrumentation, the tilt angle of the gyro is chosen to provide accurate correction for a selected nominal value of the elevation prediction component.

The coupling between the deflection and cross-roll (gun-line) axes provided by the tilted gyroscope results in a deflection cross-roll correction for targets going from right to left as well as from left to right. When the target moves from right to left, the turn angular velocity of the fighter is opposite in sign to that shown in Fig. 11, but the roll angular velocity resulting from the turn is also opposite in sign. In making coordinated turns, the cross-roll angular velocity received by the deflection gyro is thus always opposed to the deflection angular velocity received. In the presence of cross-roll, the deflection component of prediction angle is therefore always reduced and the correct sign of deflection cross-roll correction is provided.

1:2 GUNFIRE CALIBRATION

1:2:1 General

Section 1:1 is essentially a description of the A-1 Gunsight computing mechanisms and their relation to the gunfire control problem. These mechanisms include input devices to receive available problem information and computing elements to utilize the input information and provide approximate corrections for the important fire control effects.

After the basic form of the computer instrumentation has been chosen, the overall mechanism is adjusted to yield a total prediction angle output that is as accurate as is possible with the amount of information received. This adjustment is part of a calibration program, the first step of which is to derive the computer specifications that result in a prediction computation of greatest accuracy. These specifications are called calibration standards and it is to these standards that production A-1 Gunsights are adjusted in the factory and in the field.*

In the calibration adjustment of a particular computer, the mechanism constants are set first. The speeds of the elevation and deflection gyro wheels are checked and the gyro linkages are adjusted to the correct ratio. The damper temperatures, the accelerometer lever arm, the "zeros" of the electronic elements are all made to match the values dictated by the derived calibration.

Finally the "stiffness" characteristic of the elastic restraint motors is adjusted by control of the prediction sensitivity excitation current. This stiffness current is not set to a constant value, as are the above adjustments, but is made to vary with range and air density according to a derived family of calibration curves. These important calibration curves are reproduced in individual computers by adjusting the stiffness current circuit, shown in Fig. 5, and the associated range and air density devices.

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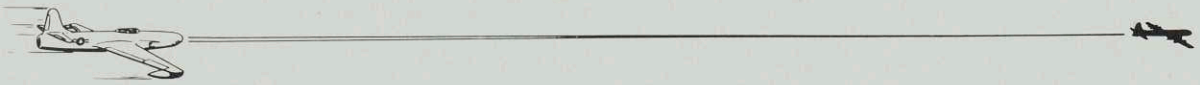
* This section deals only with the calibration of the A-1 Sight for gunfire control. Similar procedures are used, however, in the design and adjustment of the rocketfire and bombing equipment.



1:2:2 Prediction Sensitivity Calibration

The prediction sensitivity (stiffness) current greatly influences the accuracy of the total prediction angle output, since all of the A-1 Gunsight correction systems operate against the elastic restraint determined by this current. It is therefore desirable to look into the general procedure by which the prediction sensitivity calibration curves are derived.

The largest correction produced by the A-1 Gunsight is lead, and the preliminary choice of the stiffness current curves is made to satisfy this requirement. This is done by initially adjusting the stiffness of the elastic restraint to vary with range and air density so that, when operating against the torque outputs of the gyroscope and the damper, the computer shaft turns through an angle closely related to the correct value of lead. The initial choice of the stiffness current curves is later modified to satisfy more nearly the requirements of other corrections and to thereby improve the accuracy of the total prediction angle generated by the computer.

The gunfire accelerometer is next added to the elevation gyro gimbal. On the basis of the initial choice of the stiffness current curves, the mass and lever arm of the accelerometer are chosen so that it causes displacements of the computer shaft approximately proportional to elevation gravity-drop and velocity-jump corrections for both gravity and kinematic accelerations. Because these two effects are not of identical character, a satisfactory compromise is made between them in the design of the accelerometer mechanism. Other details in the mechanism design, such as the 10-degree tilt of the deflection gyro, are decided upon so that they will yield influences in proper relation to the lead, gravity-drop, and velocity-jump corrections.

With the computer mechanism designed and approximately adjusted, an important step is now taken in the calibration process. The prediction sensitivity (stiffness) current is modified to improve the accuracy of the <u>total</u> prediction angle output. In the course of this modification, allowance is made for effects, such as the deflection component of gravity-drop, for which no explicit correction mechanism is employed. This gravity correction, for example, is added to the deflection lead computation by altering the deflection computer shaft stiffness so that, with the inputs that are received, the deflection computer shaft turns through the sum of the deflection lead angle <u>plus</u> the deflection gravity-drop correction, instead of through the deflection lead angle alone.

By the procedure described, a deflection stiffness current is chosen which most nearly provides all of the desired deflection corrections, and an elevation current is chosen to most nearly provide the total desired elevation correction. In the A-1 Gunsight calibration it was found, however, that the elevation and deflection current curves, averaged over a wide variety of problem conditions (initial ranges, initial course angles, velocities, etc.), were sufficiently alike to permit the use of a single current family. A single current generating circuit, therefore, can be used to excite both the elevation and the deflection elastic restraint motors.*

The amount by which the preliminary stiffness current curves were modified to yield the final calibration standard is relatively small – less than a 10 percent change – but is nevertheless significant. At this stage of the calibration, the procedure shifts from that of making individual corrections accurate to that of making the total prediction correction accurate. Readjustments are made in the separate correction systems if these are found to improve the total output.

1:2:3 Special Characteristics of the Problem

One might well ask how, in the calibration, account is taken of effects for which no input quantity is received. The answer to this question lies in an examination of the fire control problem solved by the A-1 Gunsight. First, it is assumed that the heavy bomber target flies straight and level in the performance of its bombing mission.** Secondly, the fixed-gun fighter pilot is not free to fly any course he chooses. For any given run, in fact, he is expected to fly very close to the course that provides maximum hits on the target, this being the single course that keeps the reticle continuously encircling the target while the prediction computer generates the correct prediction angle. Thirdly, the fighter pilot is presumed to fly his plane in a coordinated manner with zero yaw and zero sidewise acceleration.

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* A brief treatment of the methods for determining optimum stiffness current requirements can be found in report R-5 "Notes For Pilots on Design & Effective Range of Operation, A-1 Gun-Bomb-Rocket Sight for Caliber 0.50 Gunfire" by J.B. Feldman and J.R. Rogers of the M.I.T. Instrumentation Laboratory. RESTRICTED, November 1950.

** This assumption also holds for high-speed fighter aircraft which cannot deviate appreciably from straight-line, constant-velocity flight because of "g" limitations.

These three characteristics of the A-1 Gunsight problem, shown in Fig. 12, tend to narrow the problem and to cause special interrelationships among the problem variables. If the pilot performs smooth and accurate tracking while his prediction computer continuously generates the required prediction angle, the fighter flies a lead-pursuit course

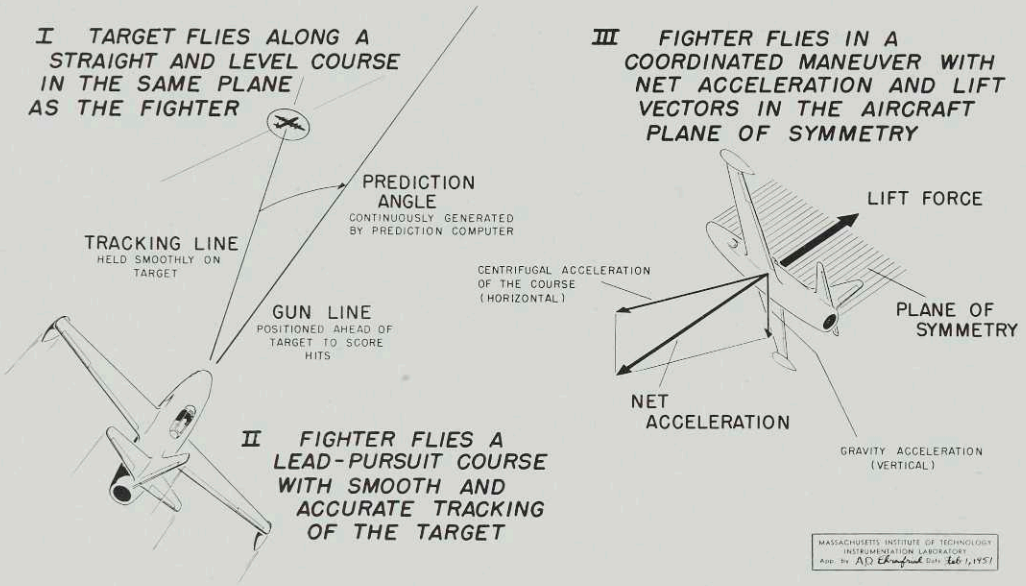
I TARGET FLIES ALONG A STRAIGHT AND LEVEL COURSE IN THE SAME PLANE AS THE FIGHTER
PREDICTION ANGLE
CONTINUOUSLY GENERATED BY PREDICTION COMPUTER
TRACKING LINE
HELD SMOOTHLY ON TARGET
GUN LINE
POSITIONED AHEAD OF TARGET TO SCORE HITS
II FIGHTER FLIES A LEAD-PURSUIT COURSE WITH SMOOTH AND ACCURATE TRACKING OF THE TARGET
III FIGHTER FLIES IN A COORDINATED MANEUVER WITH NET ACCELERATION AND LIFT VECTORS IN THE AIRCRAFT PLANE OF SYMMETRY
LIFT FORCE
CENTRIFUGAL ACCELERATION OF THE COURSE (HORIZONTAL)
PLANE OF SYMMETRY
NET ACCELERATION
GRAVITY ACCELERATION (VERTICAL)
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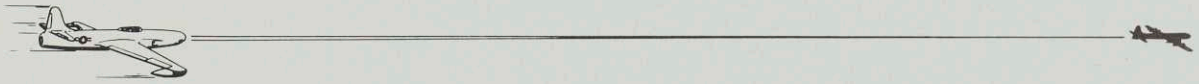
Fig. 12 THREE IMPORTANT CHARACTERISTICS OF THE A-1 GUNSIGHT PROBLEM
These narrow the problem and permit simplification of computing equipment

(more completely called "aerodynamic" lead-pursuit, since changes in angle of attack occur and are considered). Against a target assumed to move in a straight line at constant velocity, these lead-pursuit courses are basically similar even for different initial course angles, target and fighter velocities, etc. The fact that the fighter always follows a lead-pursuit course, plus the added condition that these courses are flown in a coordinated manner, results in such variables as turning rate, angle of bank, kinematic acceleration, etc. being uniformly related to one another and to important problem variables such as range.

Calibration Compromise



The result of the special relationships that grow out of the A-1 Gunsight problem is that certain variables need not be measured directly to be at least partially taken into account in the computation. These unmeasured quantities can be related to the variables that are measured. It is in this way that maximum use is made in the A-1 Sight of the input data received. During the final stage of the calibration when the stiffness current is adjusted to make the total prediction output most accurate, account is taken implicitly of the special interrelationships among problem variables.

By making use of the characteristics of the particular problem being solved, the mechanism of a fire control computer can be made simpler, smaller and more reliable. At the same time, however, the usefulness of the computer is somewhat limited in that major deviations from the assumed problem conditions may result in appreciable error. During the calibration process, a compromise must therefore be made by the designer between computer size, weight and complexity, on the one hand, and the range of operating conditions, on the other hand, over which accuracy of a specified level will be achieved.

The present A-1 Gunsight, while being designed for a particular type of air encounter, provides satisfactory gun pointing over a wide range of conditions of the problem. Acceptable performance is achieved for a variety of initial course angles, initial ranges, fighter and target speeds, etc. In addition the use of an air density detector permits the fighter to make effective attack at all operational altitudes.*

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* A quantitative evaluation of ideal A-1 Gunsight performance is given in report R-6 "Accuracy of A-1 Gun-Bomb-Rocket Sight for Caliber 0.50 Gunfire" by J.B. Feldman, R.W. Gras, and J.R. Rogers of the M.I.T. Instrumentation Laboratory. CONFIDENTIAL, December 1950.

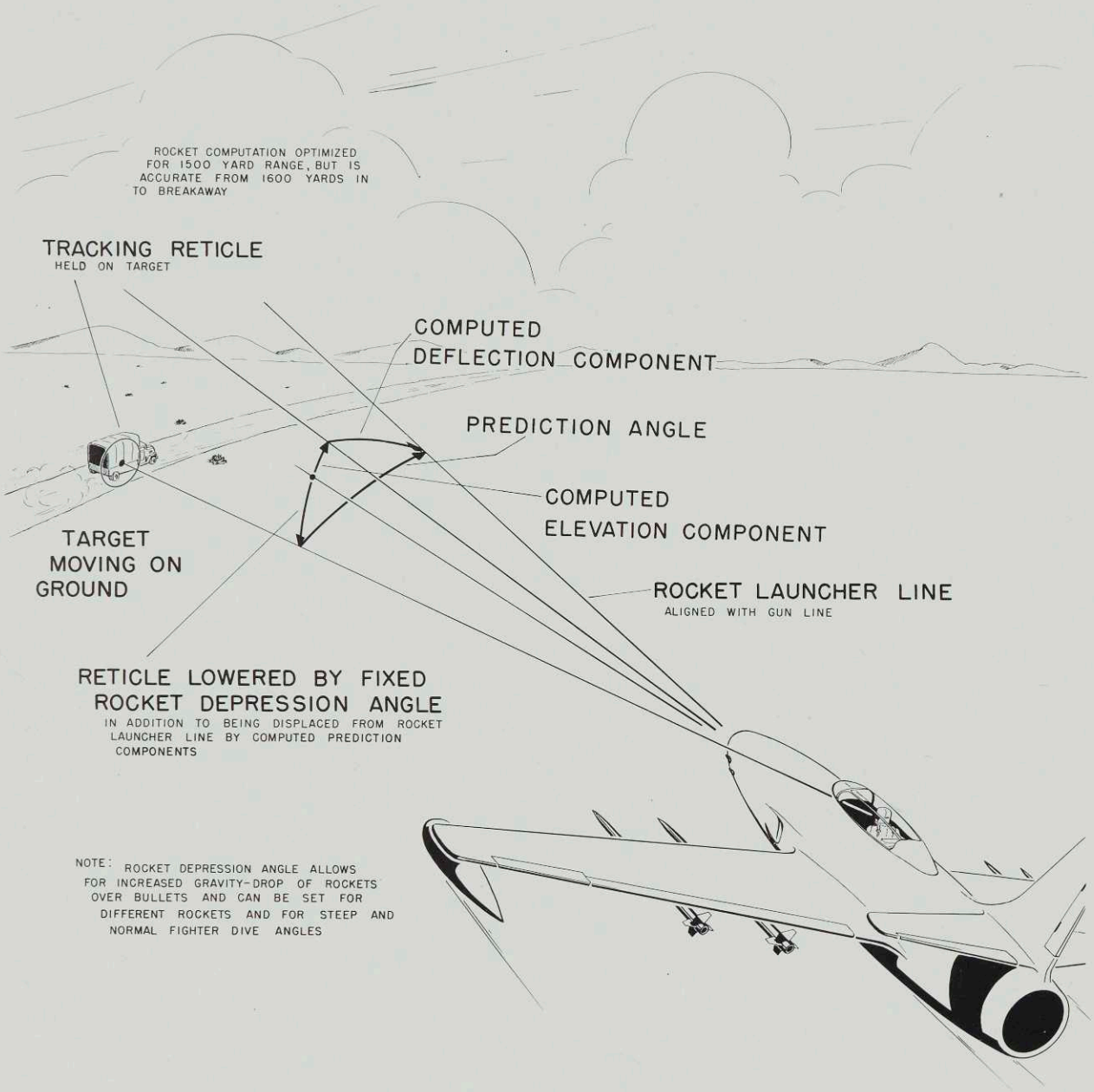
ROCKET COMPUTATION OPTIMIZED FOR 1500 YARD RANGE, BUT IS ACCURATE FROM 1600 YARDS IN TO BREAKAWAY
TRACKING RETICLE
HELD ON TARGET
COMPUTED
DEFLECTION COMPONENT
PREDICTION ANGLE
COMPUTED
ELEVATION COMPONENT
TARGET
MOVING ON
GROUND
ROCKET LAUNCHER LINE
ALIGNED WITH GUN LINE
RETICLE LOWERED BY FIXED
ROCKET DEPRESSION ANGLE
IN ADDITION TO BEING DISPLACED FROM ROCKET LAUNCHER LINE BY COMPUTED PREDICTION COMPONENTS
NOTE: ROCKET DEPRESSION ANGLE ALLOWS FOR INCREASED GRAVITY-DROP OF ROCKETS OVER BULLETS AND CAN BE SET FOR DIFFERENT ROCKETS AND FOR STEEP AND NORMAL FIGHTER DIVE ANGLES

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Fig. 13 ROCKETFIRE WITH THE A-1 SIGHT

2. ROCKETFIRE CONTROL

The A-1 Gun-Bomb-Rocket Sight can be used to direct rocketfire against moving or stationary targets on the ground, as shown in Fig. 13. Because the radar system cannot pick out specific targets against ground return, radar information is not available for the rocket computation. The A-1 Rocket Sight therefore operates with a fixed range setting chosen to provide optimum aiming at a range of 1500 yards. The rocketfire computation is relatively uncritical to the range input and thus provides accurate rocket pointing from 1600 yards in to the break-away point.

Operation of the A-1 Sight for rocketfire differs from gunfire operation in two ways:

(a) The prediction sensitivity current is held constant for the particular type of rocket being fired. This is done because of the lack of continuous radar range information and because air density, the other input to prediction sensitivity (Sec. 1:1:1), remains essentially constant for operation against ground targets.

(b) To the computed output of the elevation prediction system is added a fixed angle to allow for the increased gravity-drop of rockets over bullets. This fixed angle causes a depression of the sighting reticle and is called the "rocket depression angle" (RDA). It is set for the type of rocket being used and for the dive angle of the fighter aircraft, a "normal" dive being from 0 to 40 degrees and a "steep" dive from 40 to 60 degrees.

With the two exceptions cited above, the elevation and the deflection prediction systems operate as they do for gunfire control and provide lead, gravity-drop, velocity-jump and cross-roll corrections. Rockets can be launched when there is a wind velocity and when the target is moving on the ground, since the elevation and deflection lead systems generate corrections for such relative motion effects.

The rocket depression angle is introduced to the tracking reticle by fixed settings of an RDA pickoff which is in series with the pickoff on the elevation computer shaft. The input to the elevation mirror servo is the sum of the two pickoff outputs and is thus the sum of the computed elevation prediction angle plus the fixed rocket depression angle. For gunfire and bombing, the RDA pickoff is not used and consequently is shorted out.

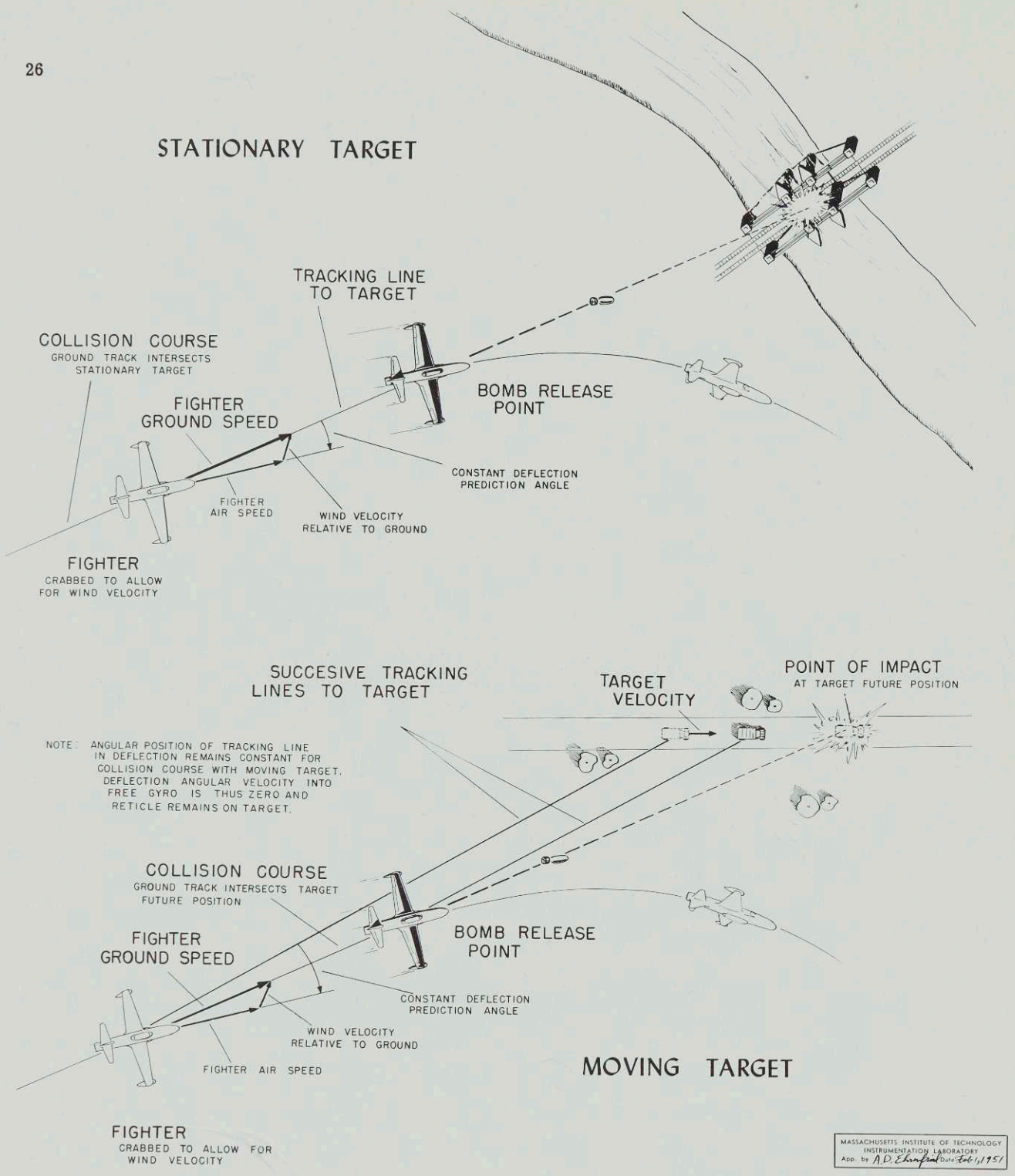
STATIONARY TARGET
TRACKING LINE TO TARGET
COLLISION COURSE
GROUND TRACK INTERSECTS STATIONARY TARGET
FIGHTER GROUND SPEED
BOMB RELEASE POINT
CONSTANT DEFLECTION PREDICTION ANGLE
FIGHTER AIR SPEED
WIND VELOCITY RELATIVE TO GROUND
FIGHTER
CRABBED TO ALLOW FOR WIND VELOCITY
SUCCESIVE TRACKING LINES TO TARGET
TARGET VELOCITY
POINT OF IMPACT
AT TARGET FUTURE POSITION
NOTE: ANGULAR POSITION OF TRACKING LINE IN DEFLECTION REMAINS CONSTANT FOR COLLISION COURSE WITH MOVING TARGET. DEFLECTION ANGULAR VELOCITY INTO FREE GYRO IS THUS ZERO AND RETICLE REMAINS ON TARGET.
COLLISION COURSE
GROUND TRACK INTERSECTS TARGET FUTURE POSITION
FIGHTER GROUND SPEED
BOMB RELEASE POINT
CONSTANT DEFLECTION PREDICTION ANGLE
WIND VELOCITY RELATIVE TO GROUND
FIGHTER AIR SPEED
MOVING TARGET
FIGHTER
CRABBED TO ALLOW FOR WIND VELOCITY
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Fig. 14 METHOD OF A-1 SIGHT BOMBING IN DEFLECTION

With tracking reticle held on target, deflection gyroscope operating against zero elastic restraint places fighter on collision course

3. BOMBING OPERATION

For the bombing of ground targets, the A-1 Sight operates in a quite different manner than for gunfire and rocketfire. A bomb is essentially a missile with zero muzzle velocity and must be released on a free-fall trajectory that intersects the target. The A-1 Sight guides the fighter during the bomb run and automatically releases the bombs when the correct release point is reached. Since the deflection and elevation bombing systems operate in different fashions they are described separately.

3:1 DEFLECTION BOMBING SYSTEM

When the A-1 Sight is switched to BOMB, the prediction sensitivity current is made zero and the deflection computer operates with zero elastic restraint. Without restraint, the deflection gyroscope is free to turn the computer shaft in response to deflection angular velocity inputs, being opposed only by the action of the viscous damper.

The fighter pilot tracks the target in deflection and adjusts the direction of his aircraft until the tracking reticle holds steadily on the target. The reticle ceasing to drift from the target indicates that the deflection gyroscope is receiving a zero angular velocity and that the fighter is on a collision course with the target in deflection. Collision courses for both stationary and moving targets are shown in Fig. 14.

When the bomb is released, it is presumed that the air will cause a negligible retardation and that the free body will maintain the velocity it had at the instant of release. The bomb is thus assumed to continue on the deflection collision courses shown and to strike the target as desired. In actuality there is a small deflection bombing error, called "cross trail", which is caused by air resistance acting on the bomb. Bomb times of flight for the A-1 Sight are so short, however, that this error is negligible.

By using the deflection gyroscope as a free gyro and placing the fighter on a deflection collision course, correction is made for the total deflection (or lateral) motion of the target relative to the fighter. This relative motion may be made up of wind velocity, target motion on the ground, or both. If there is a cross-wind component, the fighter "crabs" with respect to the ground to allow for this.

3:2 ELEVATION BOMBING SYSTEM

The elevation bombing problem is to release the bombs at the instant the fighter path is tangent to the free-fall bomb trajectory intersecting the target. To solve this problem, as shown in Fig. 15, the following alterations are made in the elevation computing system when the A-1 Sight is switched to BOMB:

(a) The prediction sensitivity current is cut off and the elevation computer shaft is made to operate without elastic restraint.

(b) A large bombing accelerometer, shown in Fig. 16, is connected to the elevation computer shaft through a special linkage. This linkage is varied continuously with fighter airspeed and is adjustable for various range motions of the target relative to the air mass.

(c) When the bombing accelerometer is engaged, it exerts a torque on the elevation computer shaft, holding the shaft against the limit stop which corresponds to a downward depression of the tracking reticle. The bombing accelerometer is opposed by the torque of a fixed bias spring which tends to support the mass of the accelerometer.

(d) A fixed voltage is introduced to the elevation mirror torque motor to hold the mirror down against its limit stop. This results in a 10-degree depression of the tracking reticle.

With the tracking reticle held in elevation at a 10-degree angle of depression, the pilot is forced to fly his aircraft along a spiral course in elevation to maintain the tracking reticle on the target. As shown in Fig. 15, the curvature of the spiral bombing path becomes progressively greater. The resulting increase in centrifugal force, accompanied by a decrease in the elevation component of gravity, tends to lift the bombing accelerometer mass and to reduce the torque of the bombing accelerometer on the computer shaft. Furthermore, as the dive velocity of the fighter increases, an airspeed bellows reduces the sum of the accelerometer and bias spring torques applied to the computer shaft.

Simultaneously, the angular velocity received by the elevation gyroscope increases because of the spiral course, and the gyro torque acting on the elevation computer shaft thus increases steadily to oppose the torque of the accelerometer. When the increasing

ELEVATION BOMBING GEOMETRY

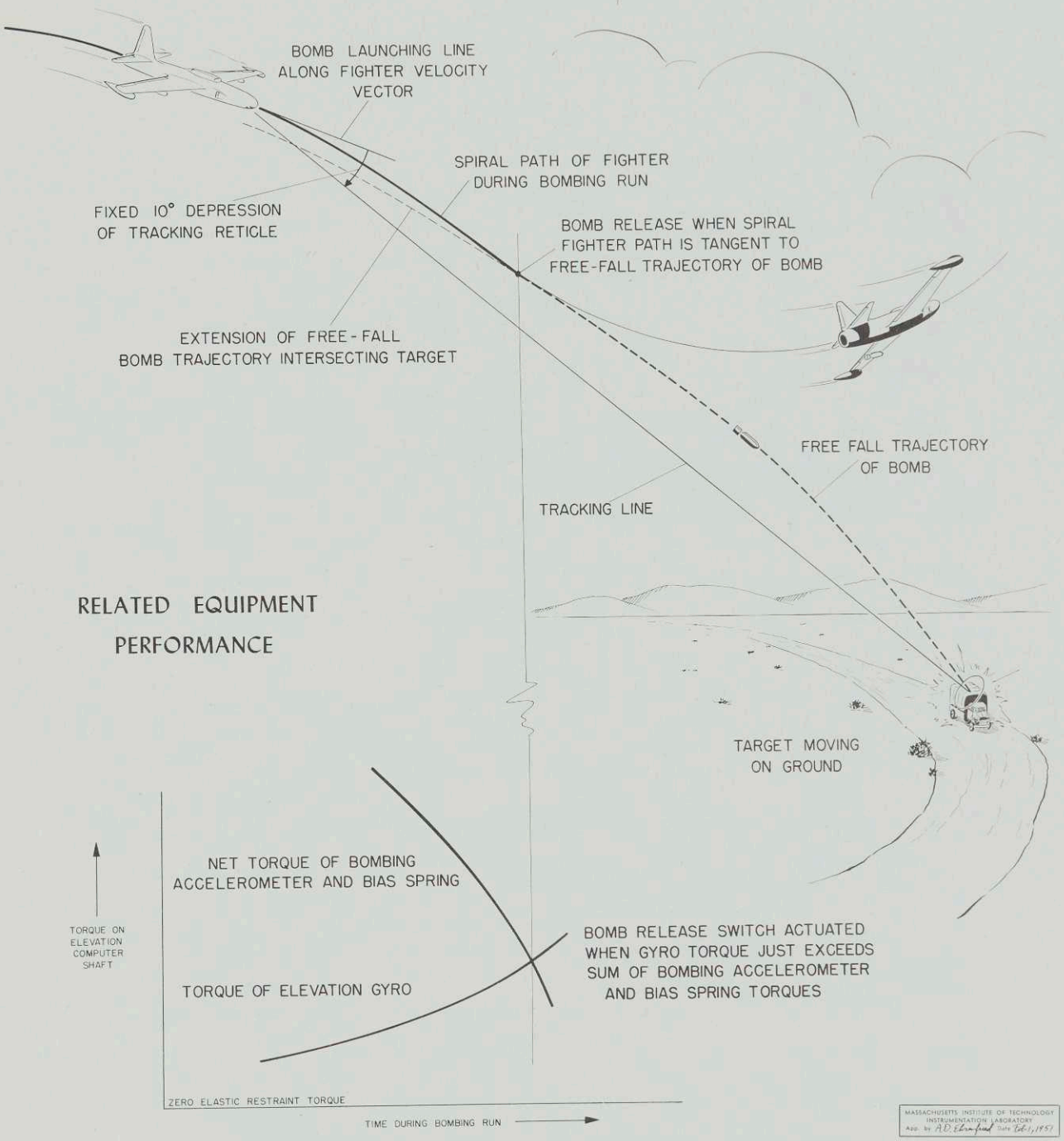
BOMB LAUNCHING LINE ALONG FIGHTER VELOCITY VECTOR
SPIRAL PATH OF FIGHTER DURING BOMBING RUN
FIXED 10° DEPRESSION OF TRACKING RETICLE
BOMB RELEASE WHEN SPIRAL FIGHTER PATH IS TANGENT TO FREE-FALL TRAJECTORY OF BOMB
EXTENSION OF FREE-FALL BOMB TRAJECTORY INTERSECTING TARGET
FREE FALL TRAJECTORY OF BOMB
TRACKING LINE
TARGET MOVING ON GROUND
RELATED EQUIPMENT PERFORMANCE
NET TORQUE OF BOMBING ACCELEROMETER AND BIAS SPRING
TORQUE ON ELEVATION COMPUTER SHAFT
TORQUE OF ELEVATION GYRO
BOMB RELEASE SWITCH ACTUATED WHEN GYRO TORQUE JUST EXCEEDS SUM OF BOMBING ACCELEROMETER AND BIAS SPRING TORQUES
ZERO ELASTIC RESTRAINT TORQUE
TIME DURING BOMBING RUN
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Fig. 15 METHOD OF A-1 SIGHT BOMBING IN ELEVATION
Torque relation which actuates bomb release is shown

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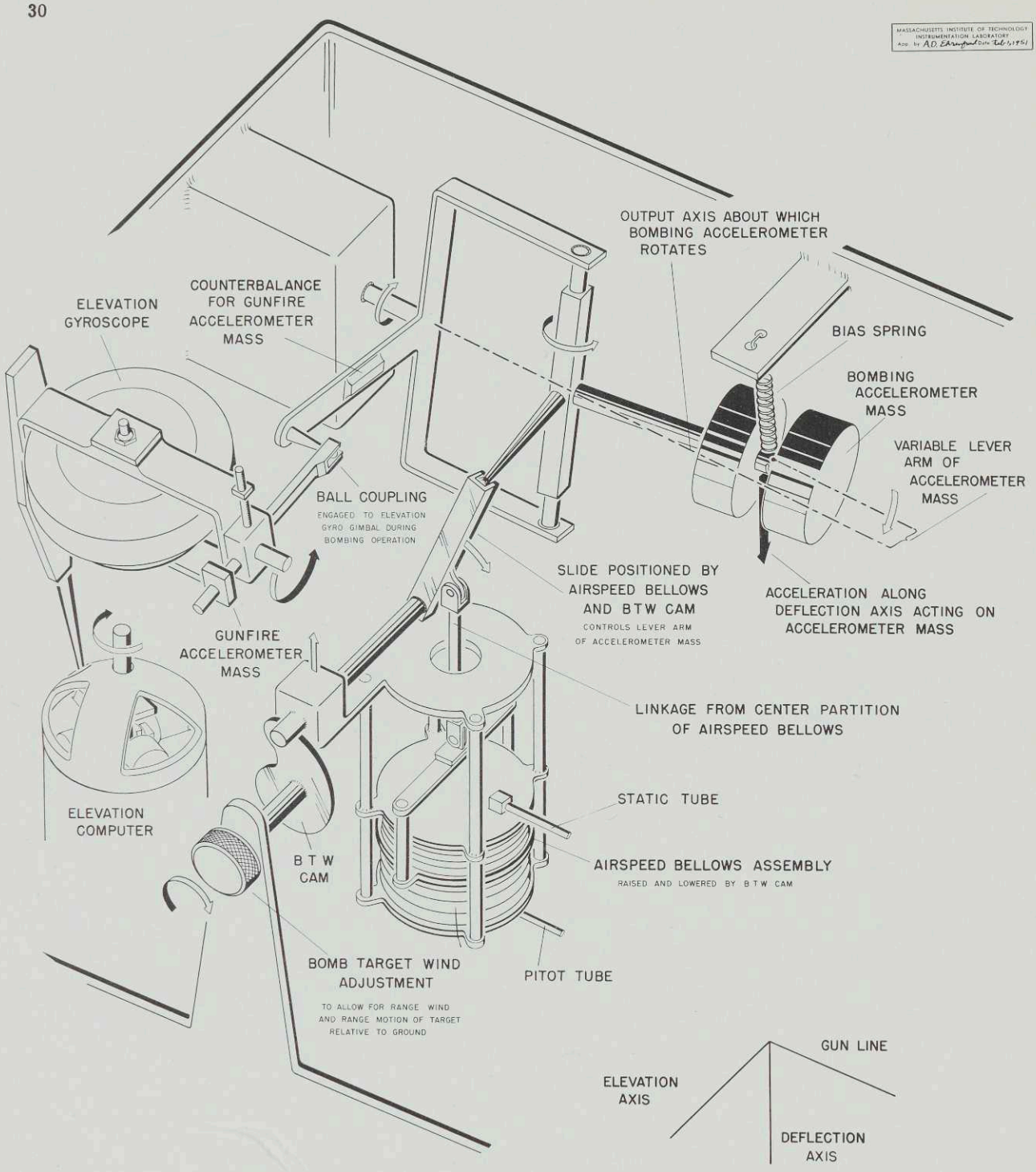
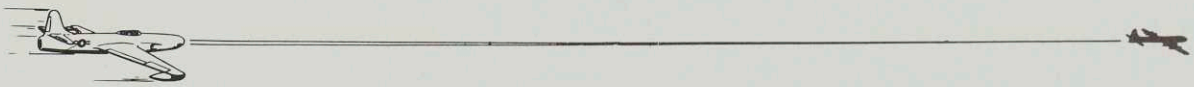

OUTPUT AXIS ABOUT WHICH BOMBING ACCELEROMETER ROTATES
ELEVATION GYROSCOPE
COUNTERBALANCE FOR GUNFIRE ACCELEROMETER MASS
BIAS SPRING
BOMBING ACCELEROMETER MASS
VARIABLE LEVER ARM OF ACCELEROMETER MASS
BALL COUPLING
ENGAGED TO ELEVATION GYRO GIMBAL DURING BOMBING OPERATION
SLIDE POSITIONED BY AIRSPEED BELLOWS AND B T W CAM
CONTROLS LEVER ARM OF ACCELEROMETER MASS
ACCELERATION ALONG DEFLECTION AXIS ACTING ON ACCELEROMETER MASS
GUNFIRE ACCELEROMETER MASS
LINKAGE FROM CENTER PARTITION OF AIRSPEED BELLOWS
STATIC TUBE
ELEVATION COMPUTER
B T W CAM
AIRSPEED BELLOWS ASSEMBLY
RAISED AND LOWERED BY B T W CAM
BOMB TARGET WIND ADJUSTMENT
TO ALLOW FOR RANGE WIND AND RANGE MOTION OF TARGET RELATIVE TO GROUND
PITOT TUBE
GUN LINE
ELEVATION AXIS
DEFLECTION AXIS

Fig. 16 AIRSPEED-CONTROLLED BOMBING ACCELEROMETER
With manual bomb target wind adjustment



gyro torque just exceeds the decreasing accelerometer and bias spring torque, the computer shaft is lifted away from its limit stop, and a switch is actuated which releases the bombs. The pilot is notified of bomb release by his circular tracking reticle momentarily turning off at the instant of release.

By design, the elevation gyro torque is made to overcome the net accelerometer and bias spring torque at the point where the spiral fighter course is tangent to the correct bomb free-fall path. The bombing accelerometer mechanism is shown in Fig. 16, and the method of continually adjusting the lever arm of the accelerometer mass by an airspeed bellows linkage is illustrated. In addition, a fixed setting of the lever arm is made to allow for the range velocity of the target relative to the air mass, which may result from the target moving on the ground or from wind velocity. This fixed setting, called the "bomb target wind" (BTW) adjustment, is also calibrated to compensate for "trail", the range effect of air resistance during the flight of the bomb.

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RESTRICTED

general
operating
principles
of the
A-1
gun-bomb-rocket
SIGHT

M.I.T. Instrumentation Laboratory